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An application of fluorescent tracer to groundwater tracking

Abstract: A well network at a potential new nuclear site in Lithuania examined a semi-confined intertill aquifer 10–19 m deep and an unconfined aquifer 4.5–9 m deep. Tracer results indicate a northwest flow direction and great hydraulic connection between observation and injection wells. Natural conditions affect tracer flow velocities.

Keywords: fluorescence intensity, flow direction, hydraulic conductivity, tracer technique, sodium fluorescein.

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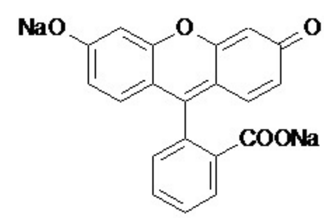
1 Introduction

Tracers are important in hydrology and hydrological research [1,2]. Reilly *et al.* [3] recognized that tracers are useful in understanding and quantifying transport processes. Magal *et al.* [4] analyzed tracers as matter carried by water which gives information concerning its direction and/or velocity as well as potential contaminant transportation. They can also help determine hydraulic conductivity [5], porosity, dispersivity [6] and other hydrogeological parameters. They are widely used but rarely applied to nuclear sites.

Flury and Wai [1] note that most common artificial tracers are salts and dyes. Fluorescent tracers (dyes) are more important because of their easy handling, simple analysis [7,8], high sensitivity, low detection limit [9] and the small quantity needed. However, they lose fluorescence due to photolytic decay. Thus, enough water needs to be spilled after injection to assure complete infiltration, and extracted water samples must be analyzed quickly and / or stored cold in darkness. Further, their use is restricted to stable chemical conditions because sorption, spectrum, and intensity are affected by pH and temperature [10].

Sodium fluorescein ($C_{20}H_{10}Na_2O_5$; uranine; Acid Yellow 73; CAS 518-47-8) is used frequently (Fig. 1); Magal *et al.* [4,11] used it to trace groundwater.



Fluorescein (uranine)

Figure 1: Sodium fluorescein.

Lithuania is planning to construct a new nuclear power plant near a closed one. Groundwater characterization is important in siting. The main aim of this work is to indicate hydrogeological parameters, flow direction, hydraulic conductivity and flow velocity using sodium fluorescein tracer.

2 Experimental procedure

2.1 Study location and geological characteristics

The potential new nuclear power plant is located near the closed Ignalina power plant in Lithuania. The closest facility is for nuclear waste storage near the site southeastern border. The nearest surface water reservoir is Lake Druksiai, where technological and cooling channels

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are close to the lake. The Visaginas public water supply is ~3.5 km southwest of the site.

This zone is composed of various Quaternary deposits and sediments. Sandy and clay loam (till) with variable hydraulic properties prevails. Bog deposits (peat) are distributed locally in depressions on the northeastern outskirts. Here groundwater merges with wetland surface water and a temporary unsaturated zone forms only in summer. In general, the unsaturated zone thickness decreases toward the north-northeast.

The monitoring well network consists of two subsystems. System I in the northwestern part of the site (Fig. 2A) consists of 8 wells: 7 observation (S1-1, S1-2, S1-3, S1-4, S1-5, S1-6, S1-7) and one injection (I1-1) [12]. The old site channel is nearby.

This well set examines the semi-confined intertill aquifer 10 to 19 m deep. The top (0.9–1.6 m) consists of technogenic soil. Moraine sandy dusty clay occurs at 4.7–6.7 m. The aquifer of medium-grained sand is below. Borehole S1-7 is installed 4 m deep in an aquifer of technogenic soil (sandy clay dust, sand, traces of organic *etc.*). The geological cross-section is shown in Fig. 2B.

System II (I2-1, S2-1, S2-2, S2-3, S2-4, S2-5, S2-6, S2-7, S2-8, S2-9 and S2-10) is placed in the unconfined aquifer at 4.5–9 m (Fig. 3A). Its geological cross-section is shown in Fig. 3B. The top layer consists of technogenic soil from 2.3 to 2.7 m, then peat (4.2–4.3 m). The aquifer of fine-grained sand lies deeper. A sandy layer pad was detected at 8.7 m in wells S2-5 and S2-10. The pad was not reached by the other wells.

2.2 Methodology

The tracer mass required (M) was estimated by Eq. 1 [10].

$$M = 10 \cdot C_B \cdot V_W \tag{1}$$

where V_W is the water volume and C_B is the apparent background fluorescein concentration. C_B (μg L^{-1}) is equal to

$$C_B = 0.01 \cdot a \tag{2}$$

a varies with tracer fluorescence intensity (a=1 for sodium fluorescein). The injection masses were 500 mg for the first system and 50 mg for the second.

Well water was mixed before sampling, the first sample was discarded, and a second 20 mL sample collected. From the first well system 630 samples were collected and 330 from the second system.

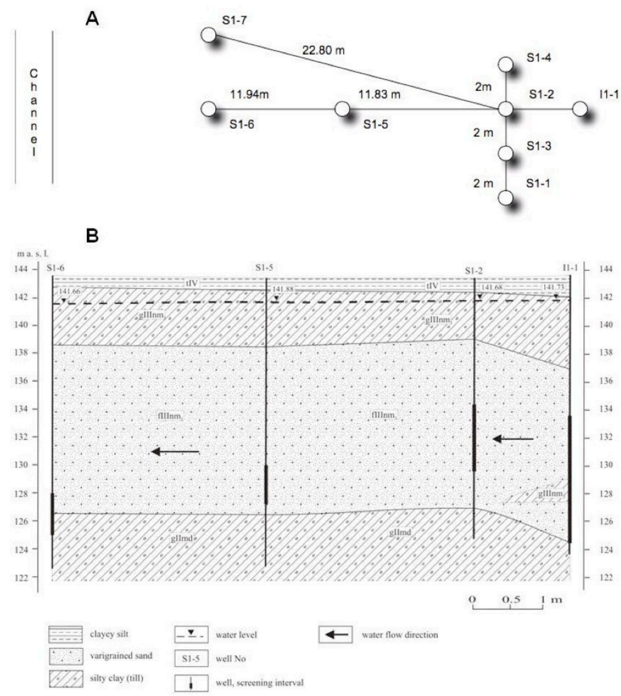

Figure 2: Scheme (A) and geological cross-section (B) of the first well system.

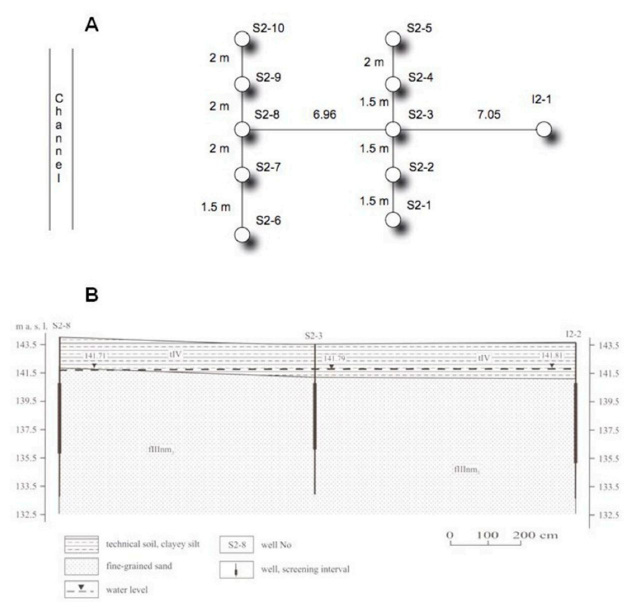

Figure 3: Scheme (A) and geological cross-section (B) of the second well system.

Fluorescence was measured in a 1-cm quartz cuvette by a computer-controlled Aminco Bowman luminescence spectrometer (Thermo Electron Corporation, USA).

Excitation was at 485 nm and emission at 513 nm. Wavelength accuracy is ±0.5 nm and repeatability ±0.25 nm.

The background fluorescence was measured in all wells before injection. Its value (0.8) depends on the fluorimeter sensitivity.

3 Results and discussion

3.1 System I

Sodium fluorescein (500 mg) was dissolved in pure water and injected in the injection well. Observation wells S1-1 to S1-4 are approximately 6 m distant (Fig. 4). Appearance was expected 8 hours after injection but no fluorescence was then detected. However, the maximum intensity occurred after 10 hours; the underground water velocity is significantly higher than expected. The highest intensity was in well S1-1 (Fig. 4), showing that the underground flow is toward the northwest. Well S1-2 is closer to the injection well but its fluorescence was not high compared to other wells. Its low intensity might be due to the difference in well screen depth. Moreover, a previously unknown morainic loam lens was found in the injection well. This impervious lens could dissipate water flow. Intensity is higher in S1-1, S1-2 and S1-4, located to the northeast and northwest.

The fluorescence in well S1-5 is shown in Fig. 5. This well is 18 m from the injection well toward Lake Druksiai. The first fluorescence measurements were performed 14 hours after injection when measurable intensity had already arisen (0.54). The maximum intensity (7.71) at S1-5 was established after 14 days. The high aquifer permeability indicates very fast groundwater flow and great hydraulic connection between the site wells.

The fluorescence in other wells during this period was not as large. The intensity oscillations may be due to natural water level fluctuations (rainfall, *etc.*) [13,14]. The maximum in well S1-5 was established after a storm. The impervious lens in the injection well may accumulate fluorescein. This concentrated fluorescein was washed from the injection well by the heavy rain. After the storm fluorescence was slightly lower.

The changes of intensity in S1-6 and S1-7 are shown in Fig. 6. Both are furthest from the injection well. The minimum was recorded after 19 days and the maximum after 33 days in S1-7.

The maximum in S1-6 was detected simultaneously with that in S1-7 showing a close hydraulic connection between this well and the injection well also, in spite of

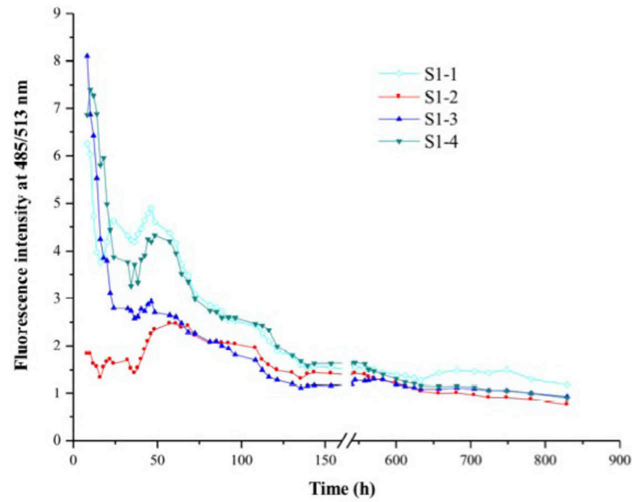

Figure 4: Fluorescence intensity in observation wells S1-1 to S1-4.

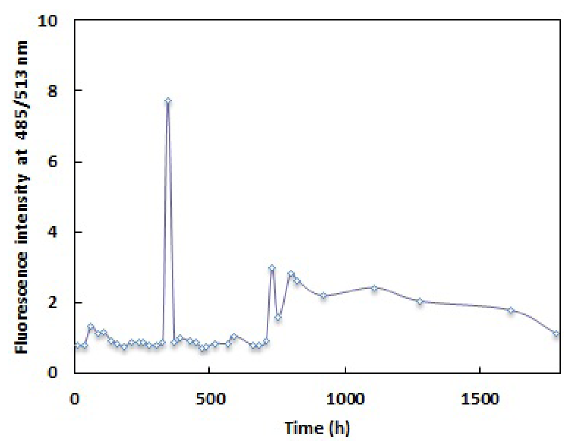

Figure 5: Fluorescence intensity in well S1-5.

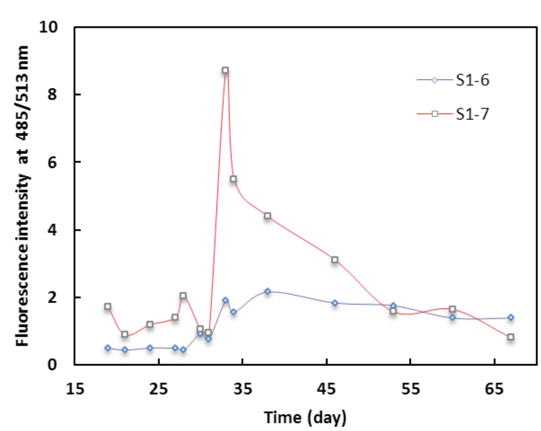

Figure 6: Fluorescence intensity in wells S1-6 and S1-7.

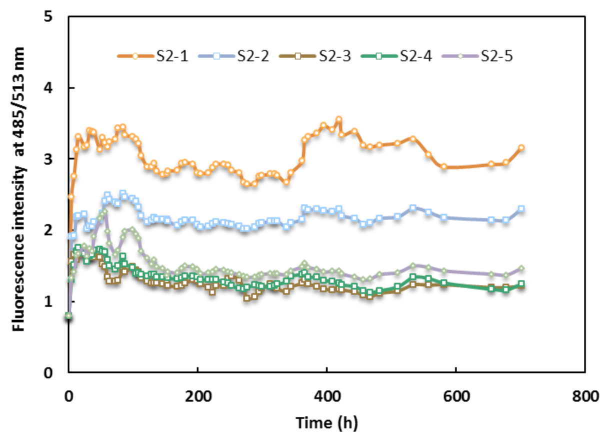

Figure 7: Fluorescence intensity in wells S2-1 and S2-5.

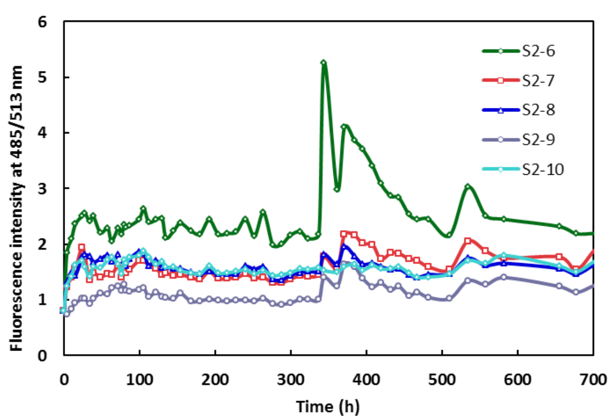

Figure 8: Fluorescence in wells S2-6 and S2-10.

the general northwesterly water flow. The aquifer is about 12 m thick in the System I area and consists of variably-grained sand. A possible difference in particle size distribution between the lower and upper aquifers may explain the higher intensity in S1-7. The sampling screen of S1-7 is between 3.6–2.1 m deep, while other well screens are between 19 and 10 m.

3.2 System II

In System II wells S2-1 to S2-5 were 7 m from the injection well. The highest fluorescence was detected in S2-1 and S2-3 (Fig. 7), suggesting that water flow is toward the NW. The same direction was found in the first system, confirming the main flow across the site. Similar fluorescence variations were observed in all wells. The intensity spikes in S2-1 to S2-5 may be due to complex site hydrogeology.

Sampling from S2-6 to S2-10 began 4 hours (Fig. 8) after injection. The distance from injection to observation wells is about 14 m.

Aquifer heterogeneity has a direct impact on hydraulic conductivity [15,16,17], which is determined by soil composition, porosity, particle size and shape, *etc.* [18]. The experimental results may be explained by a heterogeneous aquifer with different sand size distributions in the lower and upper parts. The first maximum occurred when faster transport took place through the more permeable part. The maximum fluorescence was observed after 350 hours in all wells. The highest intensity was in well S2-6. This further confirms the direction of water flow at the site - NW from the injection well toward Lake Druksiai.

The average migration velocity was 10 m d^{-1} in the deep aquifer (System I; 20 m) and 6 m d^{-1} in the shallow one (System II). These results can be used to predict groundwater contamination migration at the new nuclear power plant site in Lithuania.

4 Conclusions

A sodium fluorescein tracer experiment was performed at the site of a potential new nuclear power plant in Lithuania. Two well systems were installed. The results indicate great hydraulic connection between injection and observation wells.

Horizontal ground water migration is complicated by different sand size distributions in the aquifer. Higher fluorescence intensity was detected in wells that sampled closest to the surface. The water flow direction was northwest toward lake Druksiai.

The average groundwater migration velocity in the deep aquifer is 10 m d^{-1} and 6 m d^{-1} in the shallow one. These results can assist in predicting groundwater contamination spread at the site.

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